INVESTIGATION OF ELECTRODYNAMIC STABILIZATION AND CONTROL OF LONG ORBITING TETHERS

Contract NAS8-33691

Interim Report

For the period 1 March 1980 through 31 August 1980

Principal Investigator

Dr. Giuseppe Colombo

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Introduction

This report covers work done during the period 15 February 1980 through 15 August 1980. During the first half of this period an investigation was done on the possibility of using electrodynamic forces to control pendular oscillations during the retrieval of a subsatellite. During the last half of the period, work was shifted to studying the use of the tether for transferring payloads between orbits. Detailed results of the retrieval study are presented in Monthly Progress Report No. 5-7 and results on the launcher study are given in Monthly Reports No. 8 and 9. This report contains a summary of the work done on each project during the last six months.

Study of Electrodynamically Controlling Tether Oscillations During Retrieval

The heuristic study of using electrodynamic forces to control tether oscillations was done with a small computer program that integrates the in-plane (θ) and out-of-plane (ϕ) angles vs. time using expressions valid for small angles. To study retrieval, the general equations of motion including the radial variable r were derived and added to the program. The integration of the radial variable can be done using either a tension or a rate control law. There is strong coupling between the radial variable and the in-plane angle because the in-plane angular velocity is parallel to the orbital angular velocity which is always in the same direction and nearly constant in magnitude. This allows good control of the in-plane behavior using tension or rate control laws. The principle problem in retrieval is control of the out-of-plane angle since the coupling between the radial and out-of-plane variable is weak. The study used electrodynamic forces to control the out-of-plane angle and a rate control law to control the in-plane angle. The rate control law consisted of three terms; a term proportional to the radial distance which would maintain a constant retrieval angle in the absence of any perturbations or out-of-plane oscillations; a damping term to reduce any oscillations of the in-plane angle; and a restoring term to keep the in-plane angle near the desired retrieval angle set by the first term. The restoring term was included to counteract atmospheric drag which becomes increasingly important as the tether length decreases. Decreasing the tether length causes a coriolis acceleration which is to the rear for downward deployment, and in the forward direction for upward deployment. In order to counteract drag, the restoring term must decrease the retrieval rate for downward deployment, and increase the retrieval rate for upward deployment. In runs done for downward deployment, the restoring term halts the retrieval a few hundred meters from the Shuttle. For the upward

deployment case, drag can be counteracted longer, but the dynamics eventually becomes unstable. For either case, alternative techniques must be used to control the subsatellite close to the Shuttle. Reasonable values of current in the wire (a fraction of an ampere) appear to be capable of controlling the out-of-plane oscillations in an inclined orbit. Special considerations apply to equatorial orbits or orbits passing near the magnetic pole.

Study of Using the Tether for Transferring Payloads Between Orbits

As requested by the NASA program manager the continuation phase of this contract dealing with the use of the tether as a launcher was begun immediately upon receipt of the contract extension. The study of tether dynamics resulting from electrodynamic control has been postponed until after the launcher phase. The first task addressed was the inclusion in the Skyhook program of a thruster model for accelerating the subsatellite. It was decided to include thrusters in the directions of the in-plane angle (θ) the out-of-plane angle (ϕ) and the radial variable (r). This choice allows convenient study of in-plane and out-of-plane launches. The radial thruster was included for generality. A facility has been added to the program for specifying the three thrust components during two time periods to allow for acceleration and deceleration of the subsatellite.

Various test runs have been done with the program to gain an understanding of the dynamics of the system, particularly when the subsatellite is accelerated by thrusters. One of the most important problems that needs to be studied is potential instabilities or breakage of the tether. The initial efforts have concentrated on developing theoretical models and approximate analytical formulas for describing the behavior of the system.

One possibility for avoiding large tensions in the wire when thrusters are used is to fire the thruster in such a direction that the wire goes slack. Unfortunately, the Skyhook program is not well suited to studying a slack tether because the wire is represented by a set of discrete points. Whiplash effects are artifically exaggerated as discrete points come into tension.

There are various motions of the tether-subsatellite system that result in variations of wire tension, such as transverse wire oscillations, longitudional oscillations of the subsatellite at the end of the elastic tether, and rotational motions of the wire and subsatellite about the Shuttle resulting in coriolis forces. All of these motions can be excited by the use of thrusters on the subsatellite. The natural frequencies of the motions will depend on the system parameters. Approximate analytic expressions have been derived for the tension variations resulting from these three types of motion. The values calculated from these formulas are being compared to the data obtained in the test runs of the Skyhook program for various cases.

Transverse wire oscillations cause tension variations by changing the distance between the ends of the wire so that there is a radial acceleration of the subsatellite. The analytic expression assumes that the tension variations are small compared to the total tension. Stretching of the wire is also ignored. These assumptions are valid as long as the transverse oscillations are small and the period of longitudinal oscillations of the subsatellite at the end of the elastic wire is small compared to the period of the transverse wire oscillations. Another approach has also been used to understand the tension variations particularly when the transverse oscillations are large. A small program has been written to compute the radial acceleration of the subsatellite by numerical differentiation of the output data from the Skyhook program. This makes it possible to identify how much of the tension variations is from wire dynamics and how much is due to coriolis forces.

The following approximate expression for the wire tension has been obtained by simplifying the general equation of motion for the radial variable.

$$F_r \approx -T + m(\ddot{r} + 3mr\dot{\gamma}^2 - r\dot{\phi}^2 - r\dot{\theta}^2 - 2r\dot{\theta}\dot{\gamma})$$

If r, θ, and φ are constant, the equilibrium tension is $T = 3mr\dot{\gamma}^2$ where $\dot{\gamma}$ is the orbital angular velocity. In-plane and out-of-plane launches differ because of the last term which causes the tension to be larger for in-plane launches. The effects of transverse wire oscillations or longitudinal oscillations of the end mass show up as radial accelerations $\ddot{r}$.

In a long tether the coriolis forces are smaller for a fixed linear velocity because the angular velocity is smaller. The dynamic range of tension variations is smaller for the above reason plus the fact that the equilibrium tension is larger. If the acceleration and deceleration occur over a fixed distance, the angular amplitude of the induced transverse wire oscillation decreases with wire length. An additional problem in short tethers is that after deceleration of the subsatellite, there is little remaining tension in the wire to restrain the forward movement of the wire.

When a payload is released from the end of a tether, the system is no longer in tension equilibrium, so that the remaining mass recoils to an extent determined by the ratio of the masses before and after release. The recoil could be avoided by having the subsatellite release some wire at the launch point while keeping the tension at the equilibrium value for the remaining mass. In this way the energy stored in the stretched tether is absorbed by the subsatellite internally instead of being converted to kinetic energy. Such a system is in effect a damper. A damper with a linear restoring force and velocity dependent friction would also absorb the energy, but less efficiently. There could be loss of tension in the wire. Depending on the propagation velocity for stress along the

wire, the wire tension could also be relieved at the Shuttle end of the system. Also, a tension control law could perhaps be used for controlling other problems such as large amplitude transverse wire oscillations.

In the standard Skyhook software package, the connection between each mass point is modelled as a spring with a linear stress-strain relationship and a damping force proportional to the rate of change of distance between the mass points. The damping coefficient for each wire segment is specified on input. The only exception to this model occurs during deployment and retrieval when the tension between the Shuttle and the nearest mass point is specified by control laws. Some program modifications would be necessary in order to implement special control laws at either end of the wire.

The development of models and approximate analytical formulas for describing the dynamics of the system is continuing at the present time. The formulas are compared to results of test runs with the Skyhook program. These models and formulas will be used for designing systems and specifying system parameters for performing various types of launches.